З метою забезпечення ефективного функціонування радіометричних кореляційно-екстремальних систем навігації (КЕСН) літальних апаратів (ЛА) розроблено методи формування еталонних зображень (ЕЗ) та унімодальної вирішальної функції (ВФ). Методи розроблено для умов місцевизначення КЕСН на поверхнях візування (ПВ) з високорозвиненою інфраструктурою при незначних висотах польоту ЛА, що призводить до формування нестаціонарного за структурою поточного зображення (ПЗ). Нестаціонарність ПЗ виникає при зміні геометричних умов візування об'єктів тримірної форми. Метод формування ЕЗ ґрунтується на використанні сукупності тримірних стаціонарних об'єктів з найбільшою радіояскравісною температурою, оконтурюванні та визначенні усередненої радіояскравісної температури. Розроблено метод формування унімодальної ВФ радіометричної КЕСН, який враховує тримірну форму об'єктів ПВ, просторове положення і орієнтацію ЛА. Метод базується на здійсненні попередньої обробки ПЗ, яка полягає в його розшаруванні відносно середнього значення радіояскравісної температури фона та визначенні сукупності об'єктів з найбільшою радіояскравісною температурою. Визначена таким чином сукупність об'єктів шляхом їх оконтурювання використовується в якості геометричного інваріанта з інформативним параметром у вигляді усередненого значення радіояскравісної температури. Шляхом моделювання процесу формування ВФ встановлено, що при відношенні сигнал/шум на виході радіометричного каналу (q=5...10) формуються яскраво виражені унімодальні ВФ. При цьому забезпечується ймовірність правильної локалізації об'єкта прив'язки на ПЗ близька до одиниці, а також зменшення впливу перспективних та масштабних спотворень зображень на точність місцевизначення КЕСН.

Результати моделювання показали доцільність застосування запропонованих методів формування ЕЗ та ВФ при місцевизначенні радіометричної КЕСН на поверхнях візування із складними тримірними об'єктами, що призводять до формування нестаціонарного ПЗ

Ключові слова: кореляційно-екстремальна система, еталонне зображення, геометричні інваріанти, селективне зображення, вирішальна функція

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FORMATION OF REFERENCE IMAGES AND DECISION FUNCTION IN RADIOMETRIC CORRELATION-EXTREMAL NAVIGATION SYSTEMS

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1. Introduction

When solving problems of autonomous and noise-immune navigation of low-altitude flying machines (FM), radiometric correlation-extreme navigation systems (CENS) are widely used. However, influence of a number of factors can lead to formation of a multiextremal decision function (DF) of the CENS and worsening accuracy and probability of correct estimation of its true extremum.

Search for the objects of referencing (OR) in the current image (CI) of the sighting surface (SS) is carried out in CENS by comparing its fragments with the reference image (RI). However, sighting of complex three-dimensional objects from small altitudes and at varying angles can lead to sharp gradients of radio brightness temperature within one object. This causes appearance of new boundaries between individual elements of the object itself, displacement, blurring or new contours on the current image of the sighting surface. These circumstances cause non-stationarity of the current picture formed in the CENS. Thus, a structural mismatch appears between current and reference images which necessitates the use of other auxiliary invariant attributes of the OR image. In this connection, provision of necessary accuracy of determination of OR coordinates requires development of appropriate methods for formation of a unimodal DF. It should be borne in mind that the principles of RI building in accordance with informative attributes must comply with the CI.

The current image quality can also be affected by various obstacles, seasonal factors and adverse weather conditions causing changes in the image structure. The necessity of consideration of these factors further emphasizes relevance of the studies devoted to development of methods for formation of the unimodal decision function.

2. Literature review and problem statement

It was proposed to use reference images as binary images of contours and formation of DF to be carried out based on the analysis of fields of brightness gradients by comparing RI and CI [1]. It is considered that CI corresponds to RI by its structure and the structure itself does not depend on conditions of imaging. Formation of DF was proposed to realize using a six-dimensional grid of hypotheses of conformity of current and model images [2]. Studies were conducted for two-dimensional images without taking into account shape of objects on the sighting surface and the ratio of the object size to the width of antenna system orientation diagram. A method of localization of OR on CI in conditions of appearance of false objects during CENS position finding with the use of SS at high object saturation was developed in [3]. The work studied the effect of the current image geometric distortions resulting in appearance of false objects. That is, discrepancy between reference and current images is only determined by geometric distortions. The sighting object shape was not taken into account. Detection and localization of object contours on images was studied in [4] using the Haf transform in conditions of scale distinctions between current and reference images. The problem was solved for the case of complete conformity of morphological structure of the images being compared. Application of the theory of fractal analysis for object localization on images of various types was considered in [5]. Influence of noise on formation of two-dimensional CI was studied. The CI was considered stationary. An information-theoretical method of image processing based on entropy coding was proposed in [8]. It was shown that images of the same scene obtained in different conditions and subjected to preliminary coding show a higher correlation coefficient than original images. The image scene was described only in a plane. Methods for detecting the object contour points on segmented images formed by the method of statistical recognition of multichannel data were proposed in [7]. Influence of the factors leading to a nonstationary structure of images was not studied. Properties of invariant moments of binary images were studied in [8] for formation of their set in the problem of recognition of graphic images and measurement of distance to target objects. Contour images were considered for a two-dimensional scene. Solution of the problem of locating objects on a complex three-dimensional terrestrial scene was proposed in [9]. However, the effect of three-dimensionality of the objects themselves on emergence of nonstationary structure of the image was not studied. It was proposed to generate unimodal decision function in accordance with a minimax criterion of image similarity [10]. It was assumed that compared images conform to each other by their structure. Influence of spatiality of objects and conditions of sighting on image formation was not considered. The decision function formation with the help of descriptors with 64 elements selected based on analysis of informative attributes of the sighting surface was proposed in [11]. In this case, the result of coincidence of current and reference images was estimated using a normalized cross-correlation relative to the threshold value. Correct choice of the threshold value determines probability of reliable coincidence of the current and reference images. A structural diagram of a CENS with a built-in rapid mapping block that realizes the known approach to simultaneous positioning and mapping based on recursive Bayesian estimation was presented in [12]. It was shown that this block enables clarification of the mapping information immediately, during the flight. However, the possibility of formation of a decision function on the basis of refined cartographic information was not considered and the issue of influence of external factors on formation of refined reference images was not solved. Methods and algorithms for image segmentation according to various informative parameters were considered in [13]. The methods considered in this work allow one to form a homogeneous area based on pixel characteristics such as gray level, color, texture, intensity and other features. This enables obtaining of additional information about the area of interest in the image. However, the methods of segmentation presented in the work were considered irrespective of application fields, therefore, they need to be clarified and further developed for application in correlation-extreme navigation systems. The results of experimental studies of achievable accuracy of georeferencing by means of non-expensive radiometric hyperspectrometers were presented in [14]. It was shown that planimetric accuracy reached 4.6 m at an altitude of 344 m above ground level. This confirms just expediency of the use of radiometers in correlation-extreme navigation systems for high-precision localization when sighting objects from small altitudes. The results of development and experimental data on the use of a light unmanned flying machine with an L-band radiometer on board were presented in [15]. The experimental results show occurrence of significant errors in position finding when sighting surfaces with high object content. However, no ways of ensuring high accuracy of an unmanned flying machine position finding were proposed.

Thus, there is no solution of the problem of position finding of a CENS onboard low-altitude flying machines in conditions of formation of non-stationary current images. Besides, the necessity of ensuring the CENS operation in condition of deliberate change of CI or potential OR destruction emphasizes relevance of solution of the problem of CENS position finding in conditions of variable informational attributes.

3. The aim and objectives of the study

The study objective is position finding of the CENS used in low-altitude flying machines on the sighting surfaces with highly developed infrastructure.

To achieve this objective, the following tasks shall be addressed:

– to develop a method and algorithm for formation of reference images of three-dimensional objects of sighting;

– to develop a method and algorithm for formation of a unimodal decision function during radiometric CENS position finding with the use of a sighting surface with three-dimensional objects of sighting.

4. Development of the method and algorithm for the formation of reference images of three-dimensional objects of sighting

The task of development of the method and algorithm for formation of reference images of three-dimensional objects of sighting will be solved with the following assumptions:

1. The effect of distortion factors on the sighting surface objects is absent.
2. The size of the source image (SI) of the sighting surface: $M_1 \times M_2$, the size of the slide window $S_{SW} \in S_{SI} - N_1 \times N_2$ with coordinates of the upper corner (i, j).
3. Each i-th, j-th element of the CI is a normally distributed magnitude with a dispersion σ_{ij}^2 and an average radio brightness temperature $S(i, j)$.
4. Noise of the CENS channels is not taken into account.
5. Comparison of SI of SS S_{SI} with the formed image fragment will be carried out at a maximum value of the coefficient of cross correlation (CCC), $K_{\max}(i, j)$.

CCC of SI and the formed image fragment for all $i=1...M_1-N_1$ and $j=1...M_2-N_2$ forms a correlation analysis field (CAF). The formed CAF characterizes the degree of similarity of informative fields (IF) of the SS image fragment with the IF of other image fragments.

Let us analyze the possibility of using radio brightness contrasts between objects in a CI as an informative attribute used to form zonal structure of the image in conditions when spatial angle of the object of sighting exceeds the size of partial antenna directivity diagram (ADD).

To this end, assume that there are K objects on a SI which have radio brightness temperatures T_m and are located on a uniform background with temperature T_f. Then distribution of radio brightness temperatures in the plane of sighting will be represented as follows:

$$T_{Br}(x,y) = \begin{cases} T_m, x,y \in \overline{1,K}, \\ T_f, x,y \notin S_m = \bigcup_{m=1}^{K} S_m, \end{cases} \quad (1)$$

where $S_m \bigcap S_n = \varnothing, \quad m \neq n.$

Taking into account parameters of the antenna system, the radiobrightness temperature at the output of the T_{Aij} channel can be represented by the following relation taking into account (1):

$$T_{A_{ij}}(t) = T_f + \sum_{m=1}^{K} (T_m - T_f) \int_{S_m} G(x, y, x_{ij}(t), y_{ij}(t)) \mathrm{d}x\mathrm{d}y, \quad (2)$$

where $G(x, y, x_{ij}(t), y_{ij}(t))$ is ADD.

Expression (2) represents a model of description of the element i, j of the CI formed by radiometric channel taking into account spatial position and orientation of the flying machine. Taking into account three-dimensional form of the objects of sighting determines necessity of clarifying the T_m value in expression (2).

Taking into account influence of radio brightness temperature of atmospheric column, T_{atm}, reflected by visible parts of the three-dimensional object, radiobrightness temperature of the object of sighting, T_m, will be determined by temperatures of its individual visible surfaces. Proceeding from this, the expression for determining radiobrightness temperature of the object of a complex three-dimensional form can be represented as:

$$T_m = \frac{T_0 \sum \chi_i S_{i(\chi)} + T_{atm} \sum k_j S_{i(k)}}{S_0}, \quad (3)$$

where

$$S_0 = \sum_{i=1}^{n} S_{i(\chi)} + \sum_{j=1}^{m} S_{j(k)}$$

is the area of visible sections of surface of the object of sighting which is characterized by emissivity and reflectivity; k_j is the coefficient of reflection; T_0 is thermodynamic temperature of the object.

Relations (2), (3) make it possible to calculate the value of radiobrightness temperature in individual elements of the object of sighting taking into account its configuration. However, any section of the SS used for the position finding of the radiometric CENS of the flying machine has its own unique properties in terms of brightness, contrast, and structure. Therefore, in order to determine the informative parameter that can be used as an invariant during formation of the RI for the CENS of low-altitude flying machines, it is expedient to analyze distribution of radiobrightness temperature within the object of sighting. For this purpose, perform simulation of distribution of radiobrightness temperature between the object elements depending on sighting angles for the three-dimensional object shown in Fig. 1.

Simulation terms:

1) sighting altitude: 500 m;
2) radiobrightness temperature of the sky: 50 K;
3) thermodynamic temperature: 300 K;
4) angles of opening of radiometer ADD: 30°×40°;
5) width of partial ADD: 1°;
6) working frequency: 3.2 mm;
7) sighting corners: 90°, 60°, 45°;
8) pixel dimensions in the image: 8×8 m.

Parameters of the object of sighting:

1) three-dimensional object of a complex form (Fig. 1);
2) dimensions of the object of sighting (in nadir) 10×30 m;
3) the area of individual object elements varies according to the sighting angles;
4) emissivity of the object elements:
– horizontal platforms (concrete): 0.76;
– vertical platforms (brick): 0.82.

Background parameters:

1) material: asphalt;
2) emissivity: 0.85.

According to the results of simulation, it was found that different radiobrightness temperature gradients can be observed within one object at different sighting angles. These gradients lead to disappearance of existing and emergence of new radiobrightness contrasts and, accordingly, boundaries and contours in the object images. Thus, formation of RI with the use of boundaries and contours as invariants is inappropriate in conditions of developed infrastructure. Therefore, a necessity of search for additional informative attributes for formation of RI of SS arises.

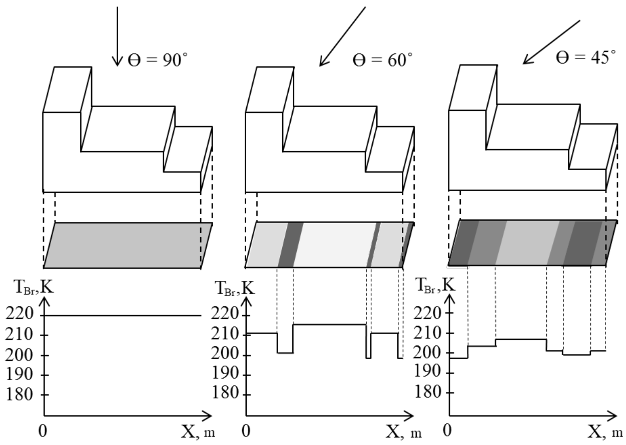


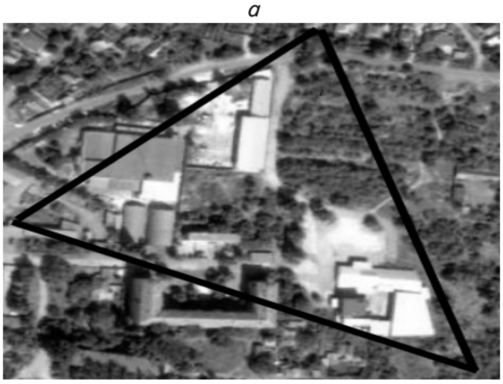
Fig. 1. Radiobrightness temperature distribution among the object elements depending on the sighting angle

It is suggested to use geometric attributes of the set of the most bright stationary objects of SS as such attributes. To this end, it is necessary to introduce the concept of geometrically connected objects through their contouring and subsequent definition of an average radiobrightness temperature for such equivalent object.

This approach makes it possible to refuse from transformation of similarity in the reference space for a large number of shifted and turned RIs to select an RI which corresponds most closely to the compared fragment when comparing with CI fragment.

Fig. 2 shows SI fragment and the objects that are defined for formation of an equivalent OR based on three bright areas of the terrain.

a



b

Fig. 2. Source image: full-size image (*a*); a fragment of SI and the objects that are defined for formation of an equivalent OR (*b*)

Let us use average radiobrightness temperature for the radiometric channel as an informative attribute of the OR introduced in this way. The contoured object and its selective image are shown in Fig. 3.

Perform formation of CAF of the contoured object and SI at radiobrightness temperature $T_{Br}(i,j)$.

Calculate the maximum value of CCC, $K_{\max}(i,j)$, corresponding to the selected images in accordance with the classical correlation algorithm for each (k, l) by the expressions:

$$K_{ij}(k,l)=\frac{1}{N_1 N_2}\sum_{m=1}^{N_1}\sum_{n=1}^{N_2} S_{KB_{ij}}(m,n)\cdot S_B(m+k-1,n+l-1), \quad (4)$$

where $K_{ij}=\left\|K_{ij}(k,l)\right\|$

$$\text{at } k=1\ldots M_1-N_1,\quad l=1\ldots M_2-N_2. \quad (5)$$

The maximum value of each resulting K_{ij} matrix which is ensured at a complete coincidence of S_{SWij} and S_{SI} is determined:

$$K_{\max}(i,j)=\max_{kl}\left\|K_{ij}(k,l)\right\|, \quad (6)$$

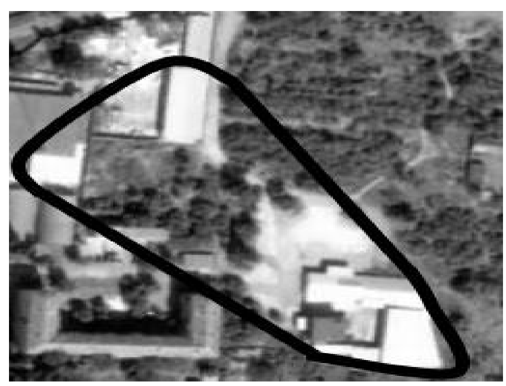
where

$$i=1\ldots M_1-N_1,\quad j=1\ldots M_2-N_2;$$

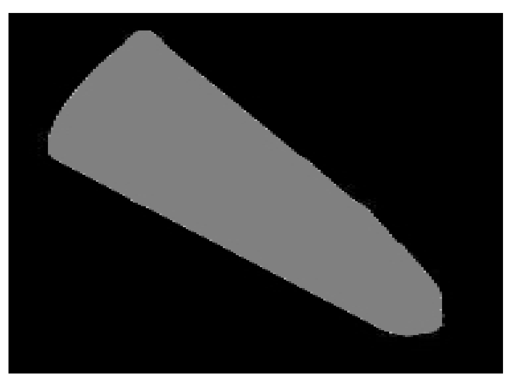
$$S_{SW}(m,n)\in S_{SS} \text{ and } S_{SI}(m+k-1,n+l-1)\in S_{SI}.$$

The matrix (2) with dimensions $(M_1-N_1)\times(M_2-N_2)$ which characterizes distribution of $K_{\max}(i,j)$ is CAF with brightness (CAF_{Br}).

The CCC resulting from comparison of the source image and the image fragment with an equivalent OR is shown in Fig. 4.



a



b

Fig. 3. Image of SI fragment: with contoured objects of OR (*a*); with average radiobrightness temperature within the contour (*b*)

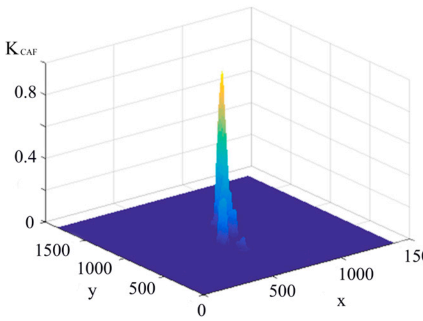


Fig. 4. CCC of the formed equivalent OR and SI

Formation of RI by means of simulation was carried out in accordance with the algorithm of formation of the set of RIs for CAF presented in Fig. 5. Comparison of RI with the source image was carried out in accordance with the classical correlation algorithm. During simulation of SI, a radiometric image was taken. It was obtained by radiometric channel from altitude of 1,000 m at sighting angle of 60°.

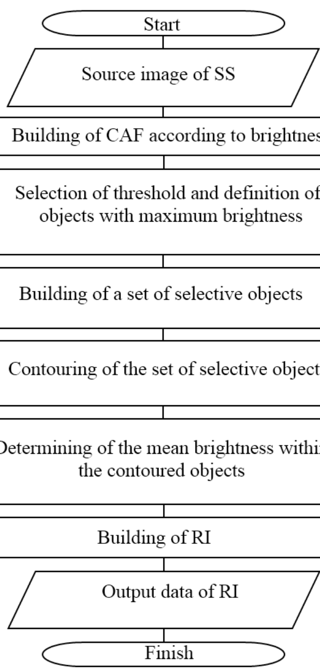


Fig. 5. Block diagram of the algorithm of formation of the set of RI for CAF_{Br}

Thus, the results of simulation of comparison of RI fragment with the use of geometrically connected objects with SI of SS confirmed effectiveness of the proposed method for formation of RI for radiometric CENS.

It has been established from the simulation results that in the case of the use of an equivalent OR, the DCF is unimodal. At the same time, complete coincidence of RI fragment with SI ensures that there is no impact of scale and perspective distortions of the SS objects on the comparison results. This is confirmed by the geometric construction of shift, scale change, perspective distortions, and SI turn with an equivalent OR relative to RIs shown in Fig. 6.

It is clear from the geometrical constructions shown in Fig. 6 that geometric distortions will be absent and unimodal decision function will be formed only in the case of full coincidence of CI fragments with RI.

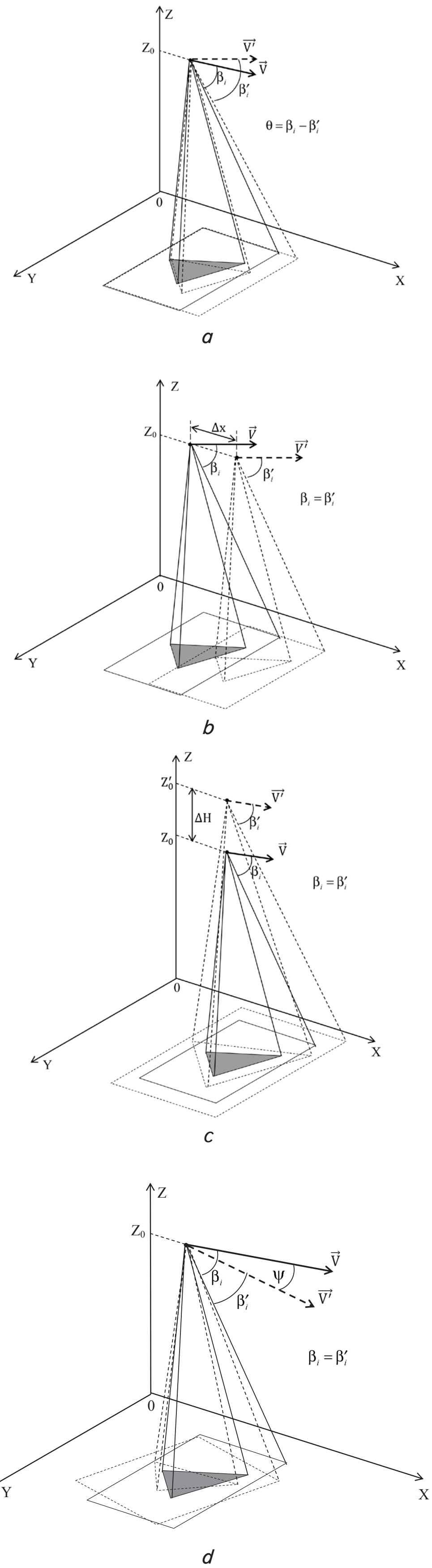


Fig. 6. Factors influencing accuracy of superposition: perspective distortion (*a*); CI bias relative to RI (*b*); turn of CI relative to RI (*c*); scale changes of CI (*d*)

5. Development of the method and algorithm for formation of unimodal decision function of the radiometric CENS

Formation of a unimodal DF requires CI preprocessing in order to reduce the latter to a form close to RI.

According to radiometric CI, this means that its processing results in a necessity of determining a set of objects in the image with the highest value of radiobrightness temperature $T_{Br}(i, j)_{\max}$. On the basis of the set, an equivalent OR will be formed later as shown above and accordingly, a new CI.

To do this, determine the average value of radiobrightness temperature of the background part of the image, $T_{Br\ av}$, and quantize radiobrightness temperatures of the objects in the current image taking into account radiometer sensitivity, ΔT, and dynamic range $T_{Br}(i, j)_{\max}-T_{Br}(i, j)_{\min}$. When quantizing, the values of the selected gray levels will be determined by the number of selected intervals, k.

Let us quantize radiobrightness temperatures of CI by breaking the temperature range $T_{Br}(i, j)_{\max}-T_{Br}(i, j)_{\min}$ in even intervals, ΔT_{Br}:

$$\Delta''_{Br} = \frac{T_{Br}(i,j)_{\max} - T_{B_{av}}}{k}, \tag{7}$$

where k=10...20 is the number of quantization levels; $\Delta T_{Br} > \Delta T$.

In accordance with the defined maximum values of radiobrightness of the objects, form the current image of $S_{CI}(M_1, M_2)$ which will be considered the source image. Calculate the average value of radiobrightness temperature for a set of bright objects and represent geometrically related objects in the image in the form of an equivalent OR with a value of brightness averaged over its plane. It is completion of preliminary processing of CI.

Next, transform CI of $S_{CI}(M_1, M_2)$ into a binary image, H, according to the rule:

$$H_i = \begin{cases} 1, S_i \in S_{\max}; \\ 0, S_i \le S_\rho; \end{cases} \quad i \in \overline{1, F_0}, \tag{8}$$

where i is the number of CI fragment occupied by OR; ρ is the number of CI fragment occupied by background; F_0 is the size of the sample that forms two classes of $\mathbf{w}_i$ that do not intersect each other and correspond to the signals of the object of reference, w_u, and background, w_r.

Solve the problem of OR selection in a binary image as follows. According to the selected threshold of values of radiobrightness temperature, compare fragments of the layered current image, $H^i \subset \mathbf{H}$, with the reference image and find the fragment of CI which will have the greatest number of coincidences.

The decision rule that defines the DF consists in the following:

$$R_j = \sup_{i \in \overline{0,M}} R_i. \tag{9}$$

As a result, a unimodal DF $R(x, y, t)$ of radiometric CENS will be formed.

The index i takes as many values M as there are possible fragments shifted one relative to the other with the set configuration in frame H. If the rule (9) corresponds to several fragments, then decision on OR localization is not made.

Probability of correct OR localization will be determined as follows when using rule (9):

$$P_{;} = \sum_{j=1}^{F_u} C_{F_u}^{j} (1-\alpha)^j \alpha^{F_u - j} \left[\sum_{m=0}^{j-1} C_{F_u}^{m} \beta^m (1-\beta)^{F_u - m} \right]^M, \tag{10}$$

where α, β are errors of the first and second kind which are determined by the value of the signal-to-noise ratio; F_u is the sample size corresponding to OR; $m \in \overline{0, M}$.

The results of estimation of probability of correct OR localization using an equivalent OR with brightness averaging in accordance with a set of geometrically related objects are shown in Fig. 7. The shown dependences were constructed for OR with area of 5...50 % of the total image area.

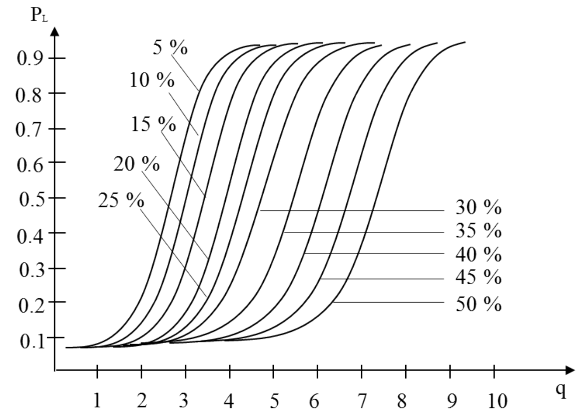


Fig. 7. Dependence of probability of correct OR localization on the signal-to-noise ratio for equivalent OR of various sizes

Thus, the developed method for formation of a unimodal DF includes the stages consisting in the following:

1) layering of CI according to the quantization threshold and determination of a set of objects with the greatest value of radiobrightness temperature;

2) construction of a selective image of a group of geometrically related objects with definition of their average radiobrightness temperature within the limits of the introduced equivalent OR;

3) formation of binary CI;

4) search for the largest coincidence of the CI fragment with the generated RI;

5) formation of DF.

Thus, it was established that the use of an auxiliary geometric attribute in the CI makes it possible to ensure probability of OR localization close to unity at a signal-to-noise ratio of 3 to 4. In this case, the area of OR must not exceed 30 % of the entire CI area.

In order to verify effectiveness of the developed method, a statistical test of the algorithm of formation of DF of radiometric CENS with the use of the RI built using a set of geometrically related objects was performed. The algorithm of formation of DF of radiometric CENS is shown in Fig. 8.

The main purpose of simulation was as follows:

– experimental confirmation of obtaining the expected value of theoretical estimation of probability of correct localization of equivalent OR by simulating the process of equivalent OR localization;

– obtaining of DF realizations as a result of correlation-extreme processing of a set of CI with OR matrix for various source data of formation of the KESN DF.

Operability of the method for unimodal DF formation was estimated using the statistical modeling method (Monte Carlo) by means of multiple restart of the computational procedures of the simulation algorithm. The total number of processed realizations used to calculate probability of correct localization of OR in CI was N_r=420.

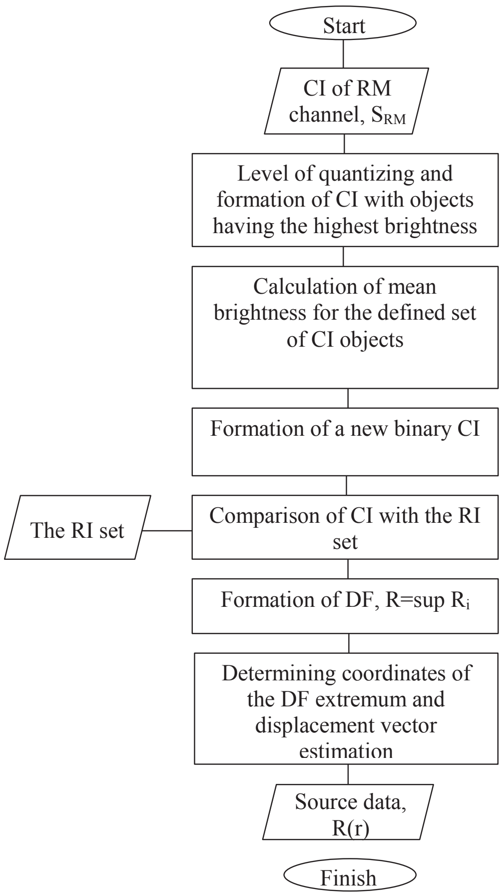


Fig. 8. Block diagram of the algorithm of formation of DF of radiometric (RM) CENS

The decision concerning OR localization is made by comparison of OR coordinates in CI as a result of statistical tests with known coordinates of OR in RI specified in the source data of simulation.

When OR coordinates in the compared images coincide, a decision is made on OR localization in CI during processing of this realization. Estimation of probability of correct localization is made by means of relation:

$$P_l = \frac{\sum_{i=1}^{N_s} P_{l_i}}{N_s}, \tag{11}$$

where P_l is the number of realizations of correctly localized OR in CI; N_s is the number of algorithm starts during tests.

The following assumptions were taken in simulation:

1) the SS scene is photographed in nadir;

2) quantization of gradations of gray levels of OR and background is completed;

3) there are no mutual turns, geometric and scale distortions of CI and RI;

4) the nodes of CI and RI matrices coincide;

5) OR is located in the center of RI.

Source data of the simulation algorithm:

Matrix of RI:

1) size: 8×8 elements;

2) informational content: binary image, OR corresponds to "1" and background to "0";

3) OR size: 3×3 elements;

4) OR form: conventional square.

Matrix of CI:

1) size: 16×16 elements;

2) the number of levels of gray quantization: OR: 5 levels, background: 0...7 levels;

3) OR size: 9 elements;

4) OR form: inscribed in a conventional square with size of 3×3.

The simulation results are presented in Fig. 9, 10.

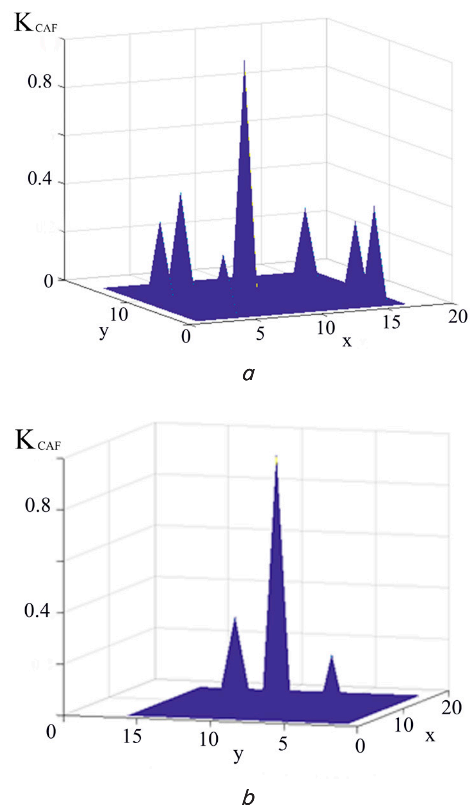


Fig. 9. CCC of CI and RI at signal/noise =10 (*a*); ratio of signal/noise =5 (*b*)

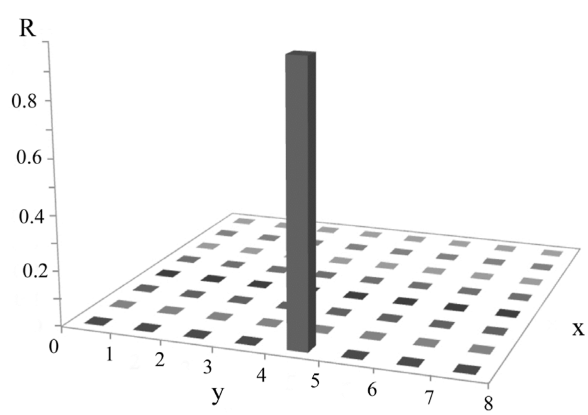


Fig. 10. The result of DF formation at signal/noise ratio of 5 to 10

Analysis of the results of statistical tests of the algorithm of formation of a unimodal DF of combined CENS using a single RI has shown the following.

1. The results of theoretical estimation of P_l coincide with the results of experimental estimation.

2. For typical values of the signal-to-noise ratio in the image (q=5...10), pronounced unimodal DFs are formed. At the same time, probability of correct localization of OR in CI is close to one.

3. Increase in the number of OR elements results in appearance of boundary effects and formation of additional surges of partial DF.

4. Increase in the number of gray gradations during CI quantization leads to formation of a distinct main extremum of the DF and appearance of additional local maxima in partial DF.

6. Discussion of results of development of the methods for formation of RI and unimodal DF by radiometric CENS

The results of theoretical studies of development of methods for formation of reference images and decision function that are the results of the authors' efforts in further development of the methods and algorithms of secondary CENS processing are presented. A number of methods for RI formation have been developed taking into account spatial position and orientation of the flying machine as well as formation of a unimodal VF in conditions of inconsistency of current and reference images. They include the method and algorithm for optical-electronic CENS position finding in CI with few bright objects that are considered to be false objects. The method is based on solution of the problem of multistage finding of position of the object of reference by determining its coordinates using the maximum value of the number of coincidences of CI fragments with RI.

However, the developed methods are not suitable for application in radiometric CENS when linking to complex three-dimensional objects when the size of the partial ADD is smaller than the size of individual elements of the object. At the same time, radiobrightness temperature gradients appear depending on the sighting angle. These gradients can lead to appearance of other interfaces between individual elements of the object itself and the new contours in the OR image. In addition, displacement or blurring of interfaces may occur which will also result in non-stationarity of the current image and its non-compliance with RI. As a result, a necessity of development of a method for RI formation taking into account changes in the structure of images depending on shape of objects and geometry of sighting appears on the one hand and a method for formation of a unimodal DF taking into account non-stationary CI structure on the other hand.

The use of auxiliary geometric attributes as invariants is the basis of development of the method for RI formation. To this end, geometric attributes of the set of the brightest stationary objects in CI having the highest radiobrightness temperature are used. For this purpose, the selected objects are contoured and subsequent definition of average radiobrightness temperature for the equivalent object is made. The objects for formation of an equivalent object are defined by constructing a field of correlation analysis using the indicator of radiobrightness temperature in accordance with a certain quantization threshold relative to the mean value of radiobrightness temperature of background. As a result, RI of the object of referencing is formed by means of binarization. Simulation of RI formation in accordance with the developed method has confirmed its high efficiency in accordance with CCC indicator.

Development of the method of formation of unimodal DF of radiometric CENS is based on CI layering and defining the objects with the highest radiobrightness temperature in accordance with the radiometer dynamic range and sensitivity. All other objects having lower radiobrightness temperature are related to background. Next, the image with a defined set of objects is binarized and compared with RI.

Verification of effectiveness of the developed method by statistical testing of the algorithm of formation of a unimodal DF of radiometric CENS using a set of geometrically related objects has shown feasibility of its application for position finding of the CENS in an SS with developed infrastructure. Complete coincidence of RI with CI ensures a minimal impact of perspective and scale distortions on the formed DF.

The methods for formation of RI and DF may be useful for navigation of flying machines at an altitude of up to 1 km. This is determined by the fact that the size of most three-dimensional stationary objects will exceed resolution of radiometric CENS. Also, the methods can be useful in the opto-electronic CENS with image quality influenced by shadows and perspective chromaticity bringing about stochasticity of informative attributes used in CI description.

In addition, it is advisable to use these methods when solving the problems of navigating the flying machines equipped with CENS, organizing jamming which may also lead to a change in the CI structure and its non-compliance with RI. But the methods may turn out to be of little use for navigating flying machines with opto-electronic CENS in conditions of reduced visibility and with restrictions on the time of formation of DF on high-speed flying machines with steep flight trajectories.

Further studies may be aimed at improving the method of DF formation in conditions of intentional change of electrophysical properties of surfaces. On the whole, the study results will be used to improve the software complex for formation of RI and unimodal DF in various conditions of CENS application.

7. Conclusions

1. A method for formation of RI of the sighting surfaces using three-dimensional objects of sighting the area of unmanned FM tie-in has been developed. The method is based on construction of binary selective images using auxiliary geometric attributes as invariants. Geometric attributes are determined by contouring a set of stationary objects with the highest radiobrightness temperature with subsequent averaging of radiobrightness temperatures within the object contour. The use of auxiliary geometric invariants provides the possibility of not taking into account changes in radiobrightness temperature which may appear between individual elements of the object itself. Estimation of quality of the formed RIs by means of modeling according to the CCC indicator has confirmed expediency of applying the proposed approach to formation of RI of CI with three-dimensional objects.

2. A method for formation of a unimodal DF of radiometric CENS which takes into account three-dimensional form of CI objects, changes in spatial position and orientation of unmanned FM was developed. The method is based on CI layering and construction of a set of binary images of the contoured object. Numerical estimates have shown that the use of geometric attributes as an invariant ensures probability of correct OR localization close to one at signal-to-noise ratio of 5 to 10. Statistical tests of the algorithm of formation of a unimodal DF of radiometric CENS in accordance with the developed method confirmed the results of theoretical studies.

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